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14. ABSTRACT

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Autonomous Micro Hopping Rotochute

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The micro hopping rotochute is a hybrid micro air/ground vehicle configuration invented specifically for long duration exploration of enclosed and tight spaces with complex terrain. The vehicle maneuvers through intricate environments by hopping over or around impeding obstacles. A small, dual rotor system provides the necessary lift while differential torque allows directional control. In addition, the low mass center and spherical exterior shape of the body creates a means to passively reorient the vehicle to an upright attitude when in contact with the ground while protecting the rotating components. Previous research associated with this vehicle configuration has included detailed flight dynamic modeling and system simulation along with an experimental testing program to verify basic flight and ground performance. While basic flight dynamic behavior of this configuration has been studied, research to date has not included autonomous control. This report details two major improvements in the hopping rotochute hybrid air and ground vehicle. The vehicle has been miniaturized by cutting the size and weight by about 1/3. The latest vehicle weighs about 68 grams and has a cage diameter of 14 cm. An autonomous hopping scheme has been created for the vehicle to enable it to automatically traverse from one point to another with a sequence of hops. The new micro autonomous hopping rotochute prototype was experimentally tested in the Georgia Tech Indoor Flight Facility. Results from experimental testing demonstrate successful autonomous operation from an initial position to a final position with good end point accuracy.

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I. Introduction

In recent military operations, both ground and air robots have demonstrated their capability to greatly aid the warfighter. Plans for future micro ground and air robots will dramatically expand missions performed by these vehicles. Success of these vehicles lies in the basic robot configuration being properly tailored to the intended application. An important mission to be tackled by future battlefield robots is exploring the interior space of caves and badly damaged buildings. While both micro ground and air vehicles offer some capability to perform these types of missions, both of these robot vehicles have notable limitations. Micro ground vehicles have difficulty traversing uneven, complex terrain while micro air vehicles do not have adequate endurance.

The hopping rotochute is a promising new hybrid ground/air vehicle that was specifically designed to robustly traverse difficult environments such as caves and damaged buildings. The exterior shape as well as the low mass center allow the hopping rotochute to always upright itself once on the ground, a feature that most current micro air vehicles are lacking. The internal mass, which is able to rotate around the perimeter of the base, allows the vehicle to hop in any given direction over obstacles which hamper typical ground vehicles. Due to the hopping method of mobility, the vehicle only uses substantial power when the rotor is powered during a hop. Once in a desired location, the aircraft requires minimal power, so in this sense the vehicle has much longer endurance, compared to conventional micro air vehicles. Previous work focused on basic flight performance of the hopping rotochute. Through the employment of a validated dynamic simulation model, trade studies showed that key parameters influencing flight performance include total system mass, rotor speed profile, internal mass weight and location, as well as battery capacity. By using the internal mass as a directional control mechanism, the trajectory of the hopping rotochute can be shaped during flight to maneuver the vehicle around large, intricate objects.

The micro hopping rotochute improves upon the original hopping rotochute in a variety of ways. The vehicle was made smaller, quieter and more robust. The original design was also improved by adding direct drive brushless motors as opposed to a brushed motor driving a transmission. This change allowed for a much simpler drive train resulting in quieter operation and fewer mechanical failures. The rotating mass used for hopping control was eliminated in favor of differential torque for yaw control, further eliminating mechanical elements of the original design. The decrease in mechanical components led to simpler construction and fewer mechanical issues. The

second major improvement to the hopping rotochute was the creation of autonomous control laws to enable automatic movement of the vehicle from an initial point to a final point. This report details these enhancements to the micro autonomous hopping rotochute, including a detailed description of the design and construction of the new prototypes as well as results from experimental flight testing in the Georgia Tech Indoor Flight Facility.

II. Design

Three conceptual design variations of the micro hopping rotochute were generated to explore different configurations of both main and stabilization rotors. The first and simplest of these designs employs a single main rotor to provide the entirety of the vehicle's thrust. To counteract the torque produced by the single rotor, a series of stators were implemented into the vehicle's base. The base also served to house all of the electrical components of the vehicle, allowing the vehicle to self-right due to the low center of gravity location. Off-setting the center of gravity in a known, horizontal direction by varying component location within the base allowed for the vehicle to attain a forward velocity. It was found through preliminary flight tests that the single rotor design induced too much torque for the stators to reliably counteract at all rotational speeds, resulting in the need to pursue other design concepts.

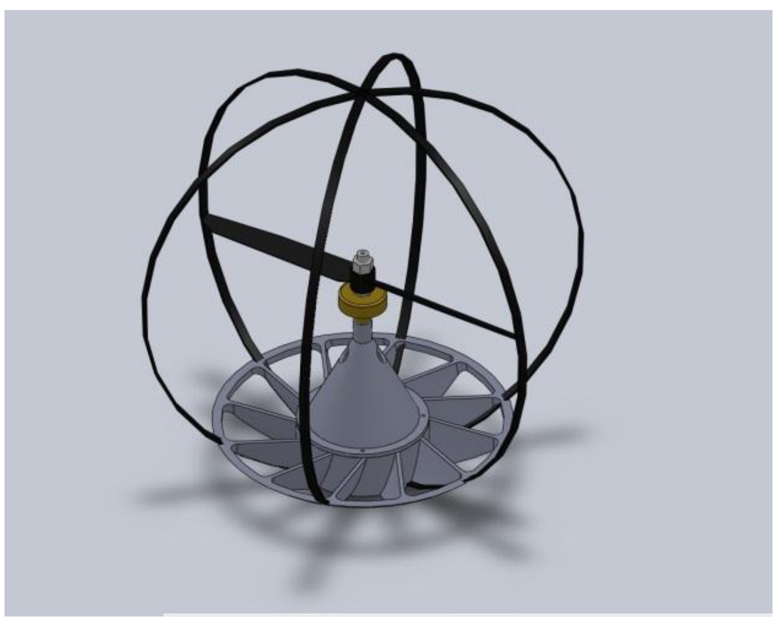

Figure 1. Single main rotor design with stators.

The second of these concepts, being the most complex of the three designs, sought to introduce torque stability via two anti-torque motors. The design followed the same form as the single rotor design, only with the smaller anti-torque motors mounted orthogonally to the main rotor on carbon fiber booms off of the electronics housing. The vehicle achieved a forward velocity and self-righting capability in the same manner as the single rotor design. After examination of the torque produced by the main rotor and the thrust produced by the anti-torque motors, it was decided that the design lacked enough merit to be pursued beyond the conceptual phase. The additional weight introduced by the anti-torque motors and their accompanying electronics solidified the decision to leave the design as just a concept.

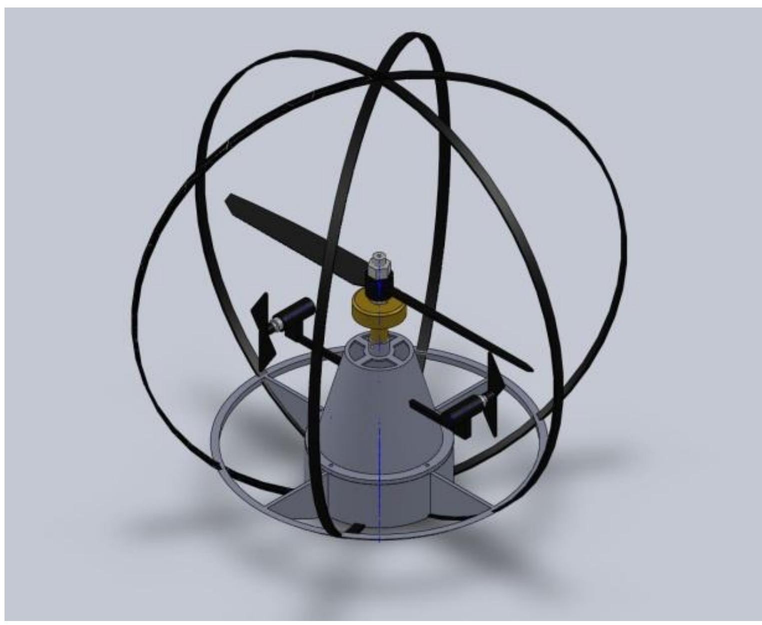

Figure 2. Single main rotor design with anti torque rotors.

A third concept is a dual rotor configuration. The dual rotors rotate in opposite directions to counteract each other's torque while generating more thrust than a single rotor system. To provide forward directional control, the center of gravity can be offset to the forward direction or the rotor axis can be tilted forward. For yaw control, differential torque can be applied by varying the relative rotational speed of the upper and lower rotors. In this design each rotor is powered by a separate motor eliminating the need for a coaxial system and a transmission. The motors are mounted concentrically and opposing each other in a support that is centered in the cage. The rotor blades used are

a set of rotors with horizontal stabilizer bars that help to prevent the vehicle from becoming unstable and tumbling. As in the previous designs, the electrical components are housed at the bottom of the vehicle in order to lower the center of gravity and self-right the vehicle. Since the dual rotor design does not have the limitations as the other concepts it was chosen as the main design and it was moved forward to the flight and control testing.

It should be noted that the first iteration of the dual rotor design did not include stabilizer bars. The original design without stabilizer bars was used for the hop tests described below, which limited the tests to small hops due to instability issues. The rotor blades with stability bars were added in after the first round of testing to fix the stability issues. The current design that includes the stabilizer no longer has this limitation and testing is in progress.

Table 1 highlights some of the significant advancements made by the dual rotor micro hopping rotochute over the original hopping rotochute.

Table 1. Design improvements over original hopping rotochute.

Characteristic	Hopping Rotochute	Dual Rotor Micro Hopping Rotochute	Units
Cage Diameter	24.1	16.5	cm
Rotor Diameter	21.3	14	cm
Mass	100	68	g
Motor Type	One Brushed	Two Brushless	n/a
Drivetrain	Transmission	Direct Drive	n/a
Control Mechanism	Internal Rotating Mass	Differential Torque	n/a
Construction Technique	Machined	Rapid Prototype	n/a

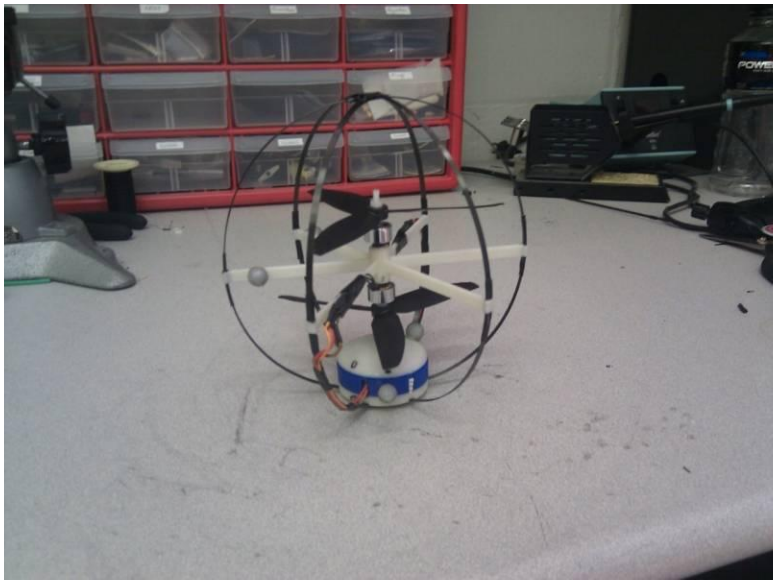

Figure 3. Counter-rotating rotor design.

III. Construction

Construction of the micro hopping rotochute began by first identifying the components necessary to bring the conceptual designs to working physical models. It was decided that the base and motor support components of each design would be fabricated using a rapid prototyping process. In combination with the rapid prototyping manufacturing technique, hard plastic was chosen as the optimal material for the rotochute base and mounting components. The process and material allowed for an extremely quick turnover between CAD design of parts and physical production. Over the course of the project, iterations of new component designs were generally received after three to four days of submission of the CAD designs. In addition to quick access to new parts, the low-density hard plastic also provided for low weight high strength parts, which were both necessary requirements for a successful design. To support and protect the hard plastic base and motor mounts, carbon fiber strips were chosen to create a spherical cage around the craft. These strong, lightweight strips are critical for the vehicle to self-right. They also serve to provide a mounting platform for the motor support, while providing protection to the vehicle from environmental objects.

Much the same as the hard plastic and carbon fiber components, it was necessary to find ultra lightweight and compact electronics to power and control the vehicle. The first of these considerations were the motors. It was

decided that brushless motors would be employed. Due to their lack of brushes when compared to a brushed motor, they are less subject to wear, showing a longer life cycle and more consistent operation. Use of brushless motors requires the use of a brushless electronic speed control (ESC) to serve as a communicator between the motor and receiver. FlightPower 6A ESC's were used due to their lightweight and small size (5.5 g, 25 x 12 x 6 mm).

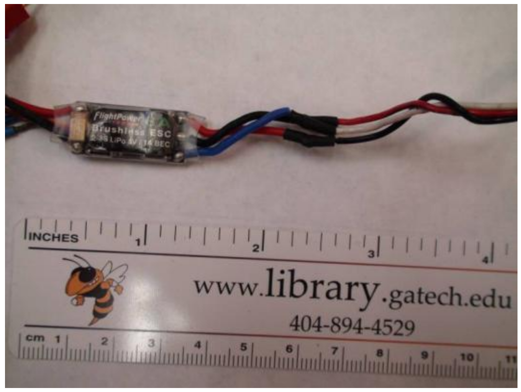

Figure 4. FlightPower 6A ESC.

It was necessary to use two ESC's for the dual rotor design, as each motor's speed needed to be controlled separately. To achieve this separate control, a multi-channel receiver was needed. The Spektrum AR6300 receiver was chosen, as it has an extremely low weight (2 g) and extremely small dimensions (28.55 x 18.35 x 2.06 mm) in addition to six independent channels.

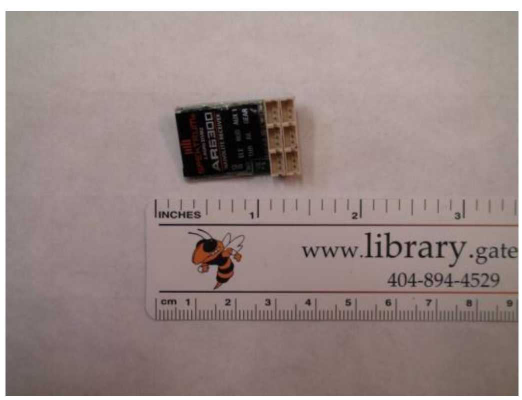

Figure 5. Spektrum AR6300 receiver.

For the battery, an Electrifly 7.4 V 200 mAh lithium polymer battery was chosen.

Figure 6. Electrifly 7.4V battery.

Each motor was connected to its own ESC, with each ESC having a separate receiver channel dedicated to it. The ESC battery connections were spliced, saving both room and weight within the electronics housing. It was necessary to only have one ESC give power to the receiver. This was achieved by simply cutting the power wire of one ESC. If both ESC power supplies are fed to the receiver, one or both of the ESC's could be damaged. The top motor ESC was connected to the throttle channel of the receiver, while the bottom motor ESC was connected to the elevator channel.

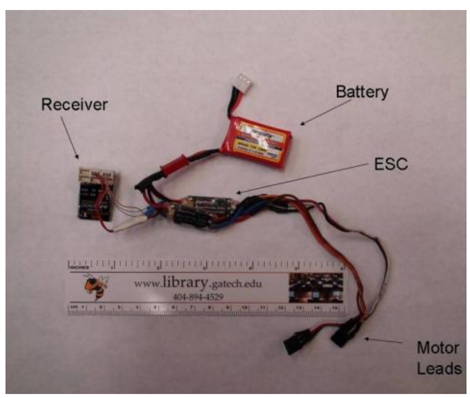

Figure 7. Complete wiring harness.

A transmitter was then used to mix the throttle and elevator channels, allowing for thrust and differential torque inputs to the vehicle. The following figures show the construction process of the vehicle.

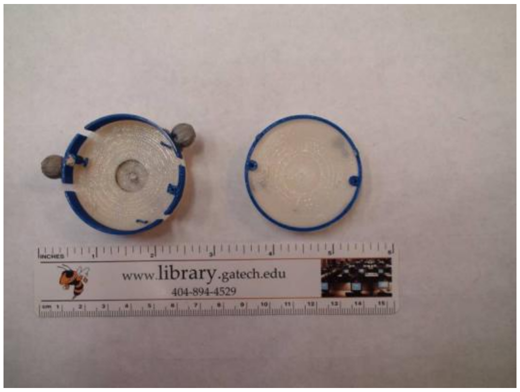

Figure 8. Rotochute base and cap.

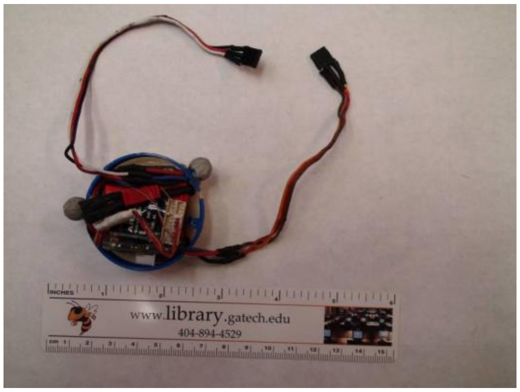

Figure 9. Combined base and wiring harness.

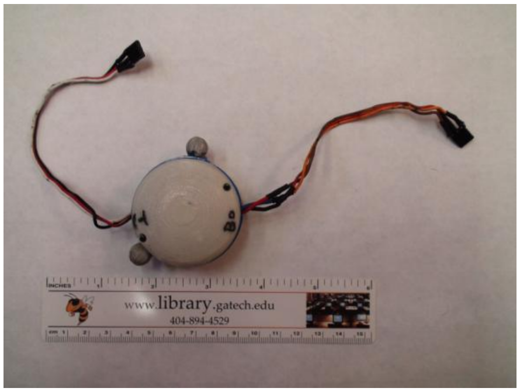

Figure 10. Closed base with wiring harness.

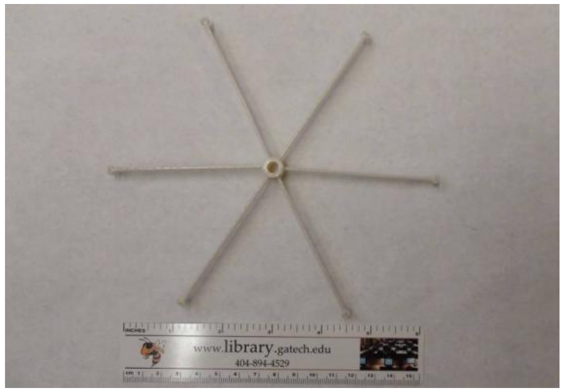

Figure 11. Motor mount.

Figure 12. Motor with rotor.

Figure 13. Assembled rotochute top view.

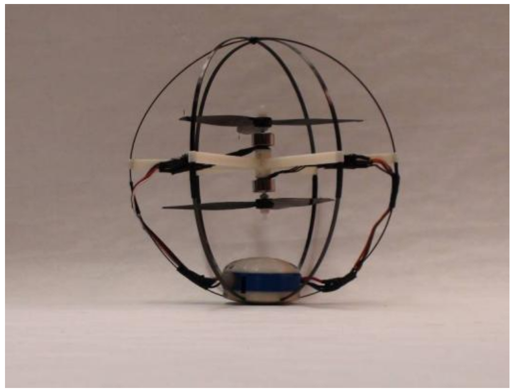

Figure 14. Assembled rotochute side view.

IV. Control Law Design

In order to control the micro hopping rotochute, an autonomous waypoint tracking controller was developed. The controller uses a Vicon motion capture lab for feedback. The lab consists of twelve motion capture cameras that track reflective markers, which when connected to a computer running Vicon's motion capture software, can stream position and orientation data in real time. The data stream in piped over the network to a computer running the waypoint tracking algorithm. After the controls are generated, they are sent wirelessly through a transmitter to a receiver on the micro hopping rotochute.

The waypoint tracking controller consists of three distinct parts, referred to within the controller as states. The first state orients the rotochute to correctly hop to the next waypoint. The second state is a transition state that allows the rotochute to settle before hoping and makes sure it is still oriented correctly. The third state performs an open loop hop. The states are repeated until the rotochute is within a set distance from the current waypoint. The control then stops, or proceeds to the next waypoint.

Figure 15 is presented to show the angles used in the control calculation. The inertial reference frame is given by $\vec{I}_I$ and $\vec{J}_I$ while the body reference frame is given $\vec{I}_B$ and $\vec{J}_B$. The hop start position is given by (x_1, y_1) while the end position is given by (x_2, y_2). The angle Ψ represents the body orientation in the inertial frame while Ψ_{hop} represents the direction of the hop relative to the body frame.

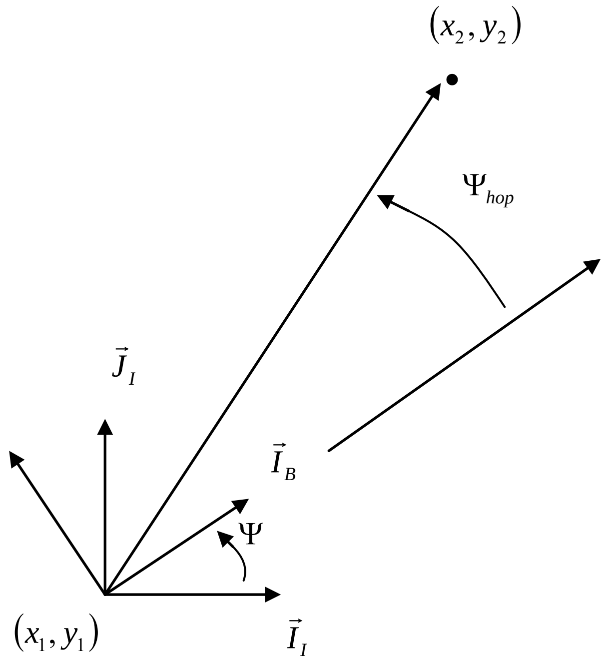

Figure 15. Angle definition for micro hopping rotochute controller.

During the first state, the commanded psi is calculated as follows.

$$\Psi_{command} = \tan^{-1}\left(\frac{y_2 - y_1}{x_2 - x_1}\right) - \Psi_{hop} \tag{1}$$

The error is psi is shown by Equation 2.

$$\Psi_{error} = \Psi - \Psi_{command} \tag{2}$$

At first, a simple proportional controller was used to orientate the vehicle using differential torque. While using differential torque, the total thrust was kept sufficiently low to keep the vehicle from leaving the ground. The simple proportional control was found to be too high at large values of Ψ_{error}. Since the control algorithm bounds Ψ_{error} bounded between $-\pi$ and π, the differential torque control input was eventually calculated as follows.

$$u_{\Psi} = k_{p_{\Psi}} \cdot 2 \cdot \sin\left(\frac{\Psi_{error}}{2}\right) \tag{3}$$

This calculation of u_{Ψ} successfully limited the control input near the bounds of Ψ_{error}. Once Ψ_{error} is located within an acceptable range, the controller moves to the second state. In the second state, the controller waits for two seconds for the rotochute to settle. If it is still within an acceptable range, the controller moves onto the third state.

During the third state, the rotochute undergoes an open loop hop. The hop is performed at full throttle for a set duration. Figure 16 provides a visual representation of the open loop hop. The rotors must first be spun up to a minimal speed to allow the brushless motor speed controllers to ramp up to full throttle quickly. This is due to the inductive sensing used by the speed controllers. The control inputs are then moved up to full throttle. The input to the second speed control is kept lower than the first in order to achieve a torque balance while hopping.

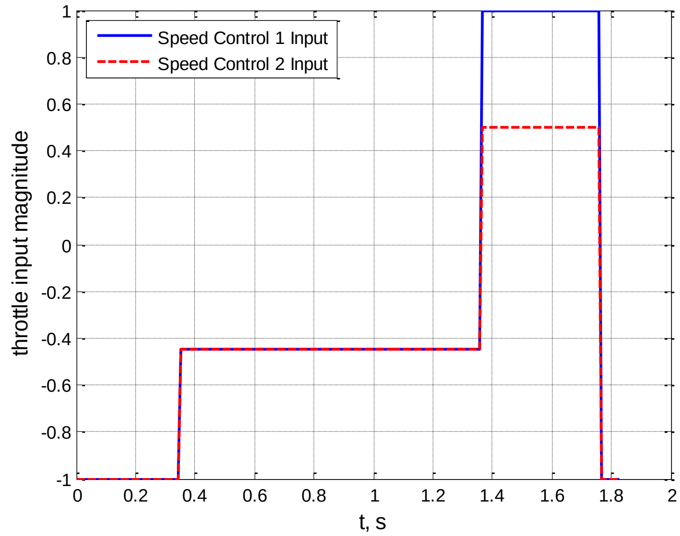

Figure 16. Example open loop control input for single hop.

At the end of the third state, Ψ_{hop} is calculated and run through a low pass filter so that an accurate value can be used for calculations in the first state. This adaptive element in the algorithm allows for variations in the rotochute from run to run to be trimmed out automatically by the controller.

V. Example Results

Using the dual rotor design with the controller explained above, many tests were run in the Georgia Tech Indoor Flight Facility. Results from an example hop, as well as a table containing a compilation of pertinent statistics are shown below.

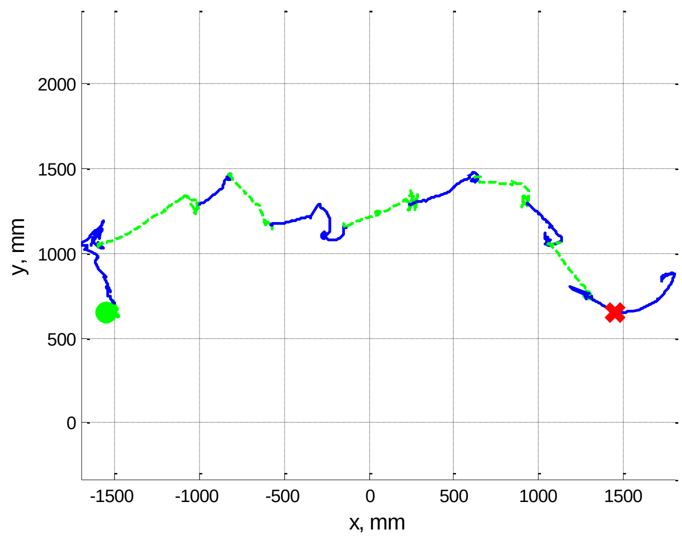

Figure 17. Y position vs X position for example hop.

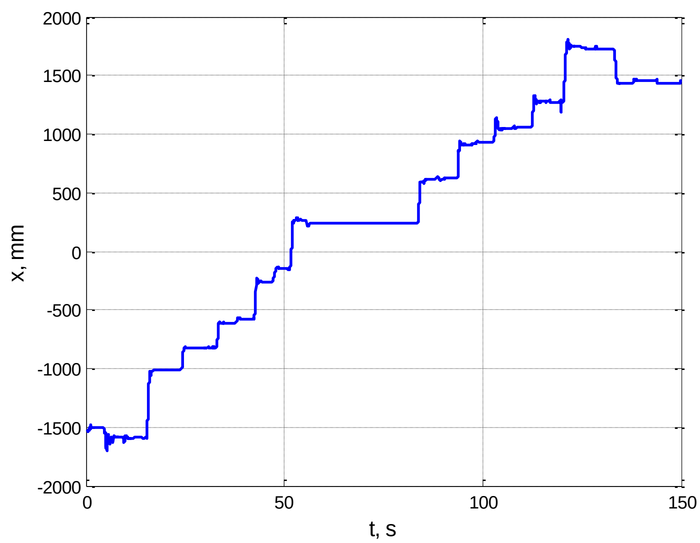

Figure 18. X position vs time for example hop.

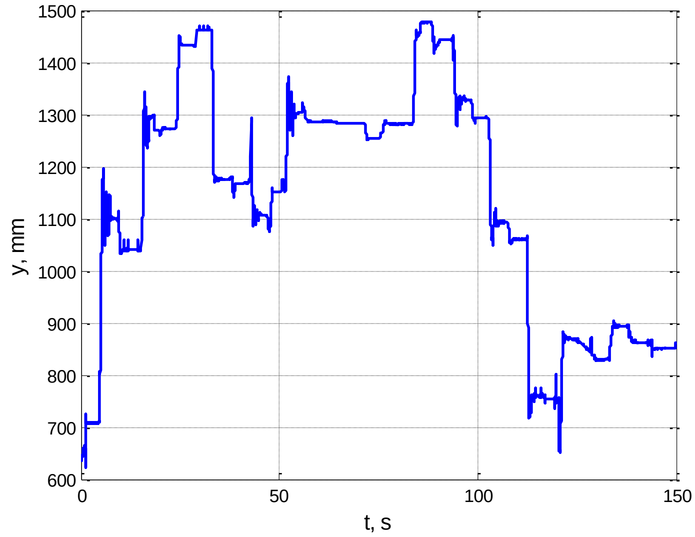

Figure 19. Y position vs time for example hop.

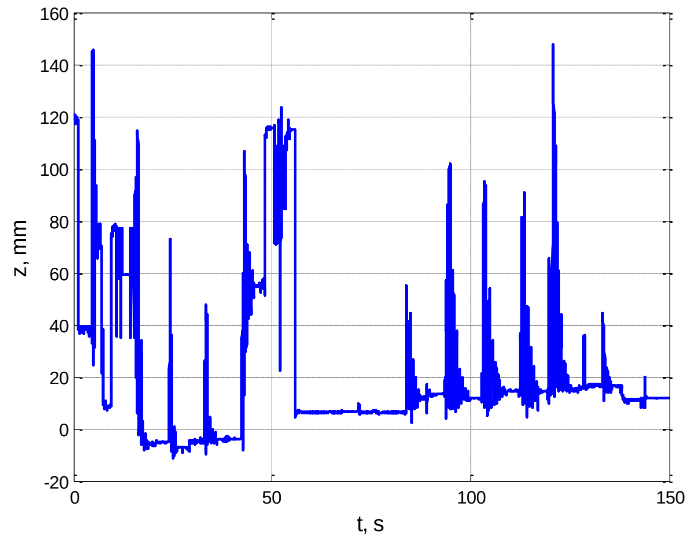

Figure 20. Z position vs time for example hop.

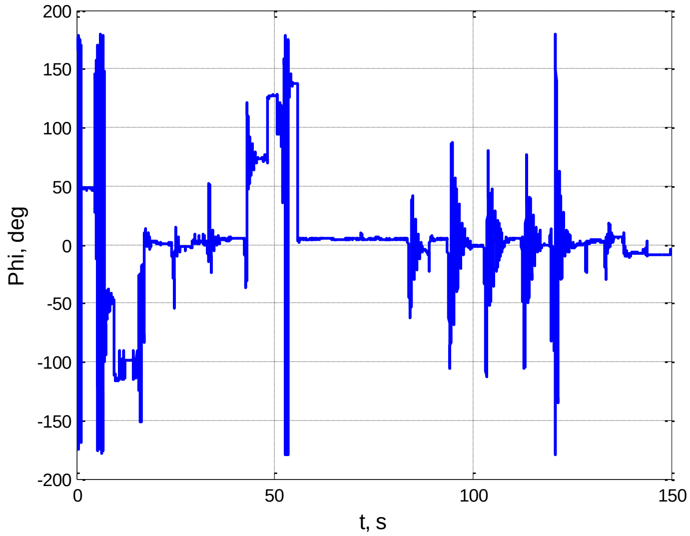

Figure 21. Roll angle, phi, vs time for example hop.

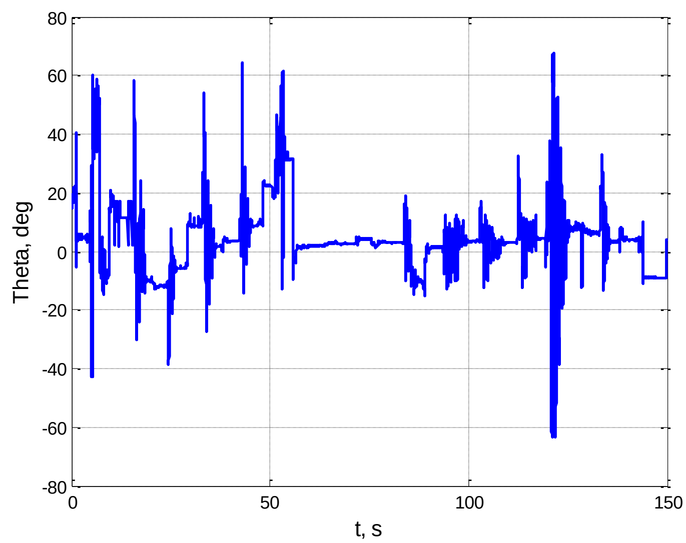

Figure 22. Pitch angle, theta, vs time for example hop.

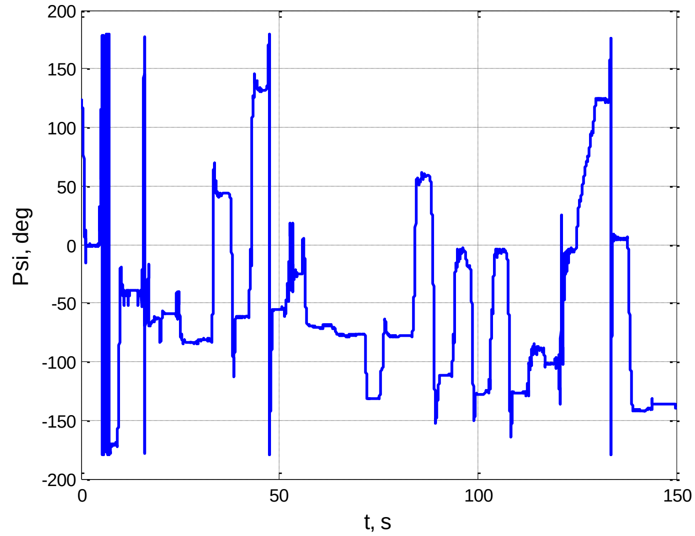

Figure 23. Yaw angle, psi, vs time for example hop.

Table 2. Autonomous Maneuver Statistics.

Number of Trials	34
X-Direction Mean Distance Error from Endpoint	138.8359 mm
Y-Direction Mean Distance Error from Endpoint	47.6917 mm
Mean Number of Hops	10.5
Standard Deviation of Number of Hops	3.3052
Mean Hop Distance	269.3895 mm

VI. Conclusion

A new small micro hopping rotochute has been created with the ability to autonomously move from one point to another in an automatic fashion. A small, dual rotor system provides the necessary lift while differential torque allows directional control. In addition, the low mass center and spherical exterior shape of the body creates a means to passively reorient the vehicle to an upright attitude when in contact with the ground while protecting the rotating components. The vehicle has been miniaturized by cutting the size and weight by about 1/3 (Weight = 68 grams,

and Cage Diameter = 14 cm). The new autonomous control law allows for pilot-free flight in the Georgia Tech Indoor Flight Facility. The smaller size of the vehicle allows for a wider variety of missions and greater flexibility during missions. Due to the mechanical simplicity of the new design compared to the original hopping rotochute, the micro hopping rotochute is much more durable and quieter. The mechanical simplicity has also led to fast construction times with fewer parts. The parts that do have to be made for the micro hopping rotochute are rapid prototyped as opposed to the original design which required parts to be machined by a machine shop. Overall, the micro hopping rotochute has been demonstrated to be a promising hybrid ground and air vehicle for applications where long endurance and low mobility is required.